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FLIGHT INVESTIGATION
TO DETERMINE THE EFFECT
OF LONGITUDINAL CHARACTERISTICS
ON LOW-SPEED INSTRUMENT OPERATION

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A flight investigation using a variable-stability helicopter was conducted under instrument flight rules (IFR) to determine the effects of gross changes in longitudinal static stability characteristics on handling qualities for V/STOL operation. Various combinations of angle-of-attack stability, speed stability, pitch-rate damping, and longitudinal control sensitivity were evaluated by means of a simulated instrument task which was selected as being representative of low-speed instrument flight.

Neutral to slightly stable angle-of-attack stability was found to be most satisfactory, regardless of the level of pitch-rate damping. Low unstable values of angle-of-attack stability were tolerable when sufficient pitch-rate damping was provided. Combinations of angle-of-attack stability and pitch-rate damping which provide minimum satisfactory handling qualities are in general agreement with current specifications for low values of angle-of-attack stability. Variations in the longitudinal control sensitivity had little effect on pilot rating over a wide range of values centered about the optimum tested.

INTRODUCTION

During the past several years, a large part of the V/STOL research effort has been directed toward exploring the relationship between handling qualities and various stability and control parameters. These investigations have been primarily concerned with the low-speed instrument flight approach which is an essential capability in realizing the full potential of V/STOL aircraft under all weather conditions. Early studies, which employed both ground-based simulators and variable-stability helicopters, were conducted to determine the effects of control sensitivity and angular-velocity damping on V/STOL handling qualities. In most instances, these control sensitivity and damping investigations were conducted in the presence of static stability levels typical of rotary-wing-type vehicles. The emergence of a wide variety of V/STOL configurations has resulted in levels and

combinations of static stability derivatives which do not fall within the range covered during previous investigations.

The present investigation, employing a variable-stability helicopter, was undertaken to expand the existing coverage of the longitudinal axis to include the effects of angle-of-attack stability and the effects of speed stability with respect to the low-speed instrument-flight-rules (IFR) task. The simulated (hooded) instrument flight task was selected to bring out the problems which would be representative of low-speed instrument flight. Various combinations of pitch-rate damping, angle-of-attack stability, speed stability, and longitudinal control sensitivity were evaluated by two NASA test pilots. Pilot comments as well as numerical ratings form the basis of the results presented in this report.

In the first phase of the flight investigation, pilot evaluations for various combinations of angle-of-attack stability and pitch-rate damping were obtained. During the remainder of the program, the effects of speed-stability and control-sensitivity variations were investigated for selected angle-of-attack stability and damping combinations.

SYMBOLS

The units used for the measurements in this investigation are given in both the U.S. Customary Units and the International System of Units (SI). Factors relating the two systems are given in reference 1.

F_{X_u} longitudinal force due to longitudinal velocity, $\dfrac{\text{lbf}}{\text{ft/sec}} \left(\dfrac{\text{newtons}}{\text{meter/sec}}\right)$

F_{Z_w} vertical force due to vertical velocity, $\dfrac{\text{lbf}}{\text{ft/sec}} \left(\dfrac{\text{newtons}}{\text{meter/sec}}\right)$

F_{Z_δ} normal force per unit displacement of height-control lever, lbf/in. (newtons/cm)

I_X, I_Y, I_Z moments of inertia about body X-, Y-, and Z-axis, respectively, slug-ft^2 (kilogram-meters^2)

M_{X_δ} rolling moment per unit stick deflection, $\dfrac{\text{lbf-ft}}{\text{in.}} \left(\dfrac{\text{newton-meters}}{\text{cm}}\right)$

M_{X_p} rolling moment proportional to rolling angular velocity, $\dfrac{\text{lbf-ft}}{\text{rad/sec}}$ $\left(\dfrac{\text{newton-meters}}{\text{rad/sec}}\right)$

M_{Y_δ} pitching moment per unit stick deflection, $\dfrac{\text{lbf-ft}}{\text{in.}}$ $\left(\dfrac{\text{newton-meters}}{\text{cm}}\right)$

M_{Y_q} pitching moment proportional to pitching angular velocity, $\dfrac{\text{lbf-ft}}{\text{rad/sec}}$ $\left(\dfrac{\text{newton-meters}}{\text{rad/sec}}\right)$

M_{Y_α} pitching moment proportional to angle of attack, $\dfrac{\text{lbf-ft}}{\text{rad}}$ $\left(\dfrac{\text{newton-meters}}{\text{rad}}\right)$

M_{Y_u} pitching moment proportional to longitudinal velocity, $\dfrac{\text{lbf-ft}}{\text{ft/sec}}$ $\left(\dfrac{\text{newton-meters}}{\text{meter/sec}}\right)$

M_{Z_δ} yawing moment per unit pedal travel, $\dfrac{\text{lbf-ft}}{\text{in.}}$ $\left(\dfrac{\text{newton-meters}}{\text{cm}}\right)$

M_{Z_r} yawing moment proportional to yawing angular velocity, $\dfrac{\text{lbf-ft}}{\text{rad/sec}}$ $\left(\dfrac{\text{newton-meters}}{\text{rad/sec}}\right)$

M_{Z_β} yawing moment proportional to sideslip angle, $\dfrac{\text{lbf-ft}}{\text{rad}}$ $\left(\dfrac{\text{newton-meters}}{\text{rad}}\right)$

m mass of aircraft, slugs   (kilograms)

p rolling angular velocity, rad/sec

$\dot{p}$ rolling angular acceleration, rad/sec^2

q pitching angular velocity, rad/sec

q_a actual pitching angular velocity of test helicopter, rad/sec

q_c commanded pitching angular velocity of the computer-model aircraft, rad/sec

$\dot{q}$ pitching angular acceleration, rad/sec^2

r   yawing angular velocity, rad/sec

$\dot{r}$ yawing angular acceleration, rad/sec^2

u   longitudinal component of velocity, ft/sec   (meters/sec)

V   resultant velocity, ft/sec   (meters/sec)

α angle of attack, rad

β angle of sideslip, rad

Δh change in altitude (positive indicates increasing altitude), ft   (meters)

$\delta_X, \delta_Y, \delta_Z$ control deflection about body X-, Y-, and Z-axis, respectively, in.   (cm)

τ time for the normal acceleration time-history curve to become concave down-
        ward, sec

DEFINITIONS

Control sensitivity: Angular acceleration resulting from unit control application; for
   example, M_{Y_δ}/I_Y in pitch, $\dfrac{\text{rad/sec}^2}{\text{in.}}$ $\left(\dfrac{\text{rad/sec}^2}{\text{cm}}\right)$.

Control power: Maximum initial angular acceleration available, rad/sec^2.

Angular-velocity damping: Angular acceleration proportional to angular velocity; for
   example, M_{Y_q}/I_Y in pitch (stable when negative), 1/sec.

Angle-of-attack stability: Angular acceleration proportional to angle of attack; that is,
   M_{Y_α}/I_Y (stable when negative), 1/sec^2.

Speed stability: Angular acceleration proportional to resultant velocity (stable when
   positive), $\dfrac{\text{rad/sec}^2}{\text{ft/sec}}$ $\left(\dfrac{\text{rad/sec}^2}{\text{meter/sec}}\right)$.

    It should be noted that, in general, speed stability is equal to $\dfrac{M_{Y_u}}{I_Y} + \dfrac{M_{Y_\alpha}}{I_Y}\left(\dfrac{\partial \alpha}{\partial V}\right)$.   In
the present investigation, the first term was obtained from the speed sensor feedback and
the second term, which represents the contribution of angle-of-attack stability to speed

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stability, was obtained from the angle-of-attack vane. For the basic aircraft, however, $\frac{\partial \alpha}{\partial V}$ is extremely small $\left(0.0008 \frac{\text{rad}}{\text{ft/sec}} \left(0.0002 \frac{\text{rad}}{\text{m/sec}}\right)\right)$. Therefore, the contribution to the speed stability from the angle-of-attack stability was neglected.

EQUIPMENT AND PROCEDURE

Test Vehicle and Simulation Technique

The variable-stability helicopter, shown in figure 1, was used in this investigation. The helicopter employs a computer-model simulation technique, a detailed description of which is given in reference 2. In this technique, a continuous real-time solution of the equations of motion which describe the characteristics of the model aircraft (i.e., the aircraft being simulated) is obtained from the onboard analog computers, and, by using closed-loop servotechniques, the test vehicle is forced to follow the computer solution.
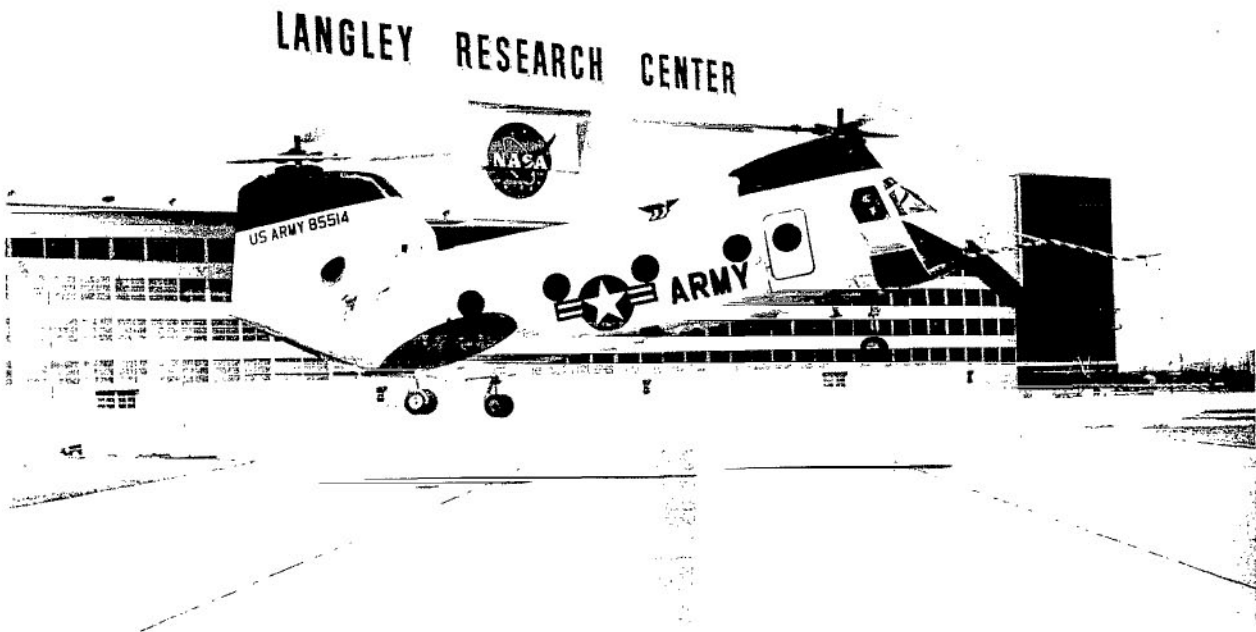
Figure 1.- Variable-stability helicopter.   L-64-2891

The mechanization of the pitch degree-of-freedom simulation is presented in the appendix, along with the equations of motion.

Task

Each of the test combinations was evaluated by means of an instrument flight task, which was developed to emphasize the effects of the different stability parameters. The task, shown in figure 2, consisted of a 9-minute hooded run, during which the pilot performed timed changes in altitude, heading, and speed. The transition into climbing or descending flight brought out the effects of angle-of-attack stability, while speed changes emphasized the effects of speed stability. The acceleration, deceleration, and turning portions of the task required the pilot to perform with a certain degree of coordination.
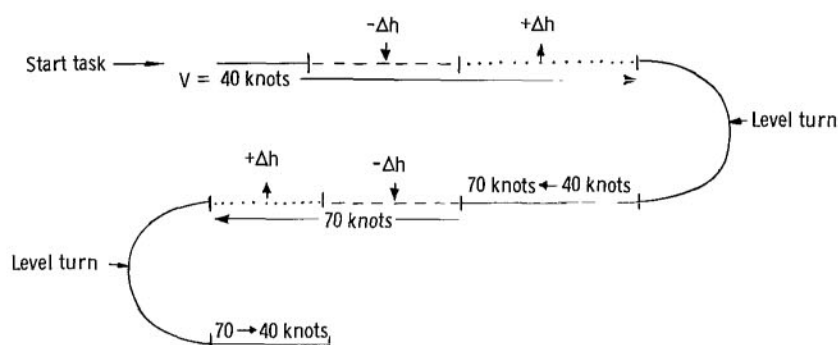

Figure 2.- Instrument flight task. $\Delta h = 500$ ft (152 m).

Atmospheric turbulence acting through both the angle-of-attack and sideslip vanes served as the disturbance source. Since the air-direction and velocity sensors are used as inputs to the computer model, disturbances sensed by the vanes and airspeed sensor generate a response consistent with the characteristics being simulated. The expanded NASA pilot-rating system shown in table I includes additional descriptive phrases which were used by the pilots to aid in their evaluation of the test configurations.

Control System

As shown in figure 3, the pilot's controls consisted of a center-mounted control for pitch and roll, rudder pedals for yaw, and a collective control for thrust. The center-mounted control had negligible friction and a spring gradient of about 1.0 lb/in. (1.8 N/cm) in both pitch and roll. The available control travel was ±6.1 inches (±15 cm) in pitch and ±6.7 inches (±17 cm) in roll, as measured at the top of the stick. However, during this study, the control power was electrically limited in both pitch and roll to 1.0 rad/sec^2. A force trim system was provided which was activated by a self-centering four-way thumb switch located at the top of the hand grip (fig. 3). The maximum trim-rate

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capability was approximately 1.0 in./sec (2.5 cm/sec). The trim motor was not equipped with a braking mechanism; the effect of this characteristic on the results of this study will be discussed in a subsequent section.
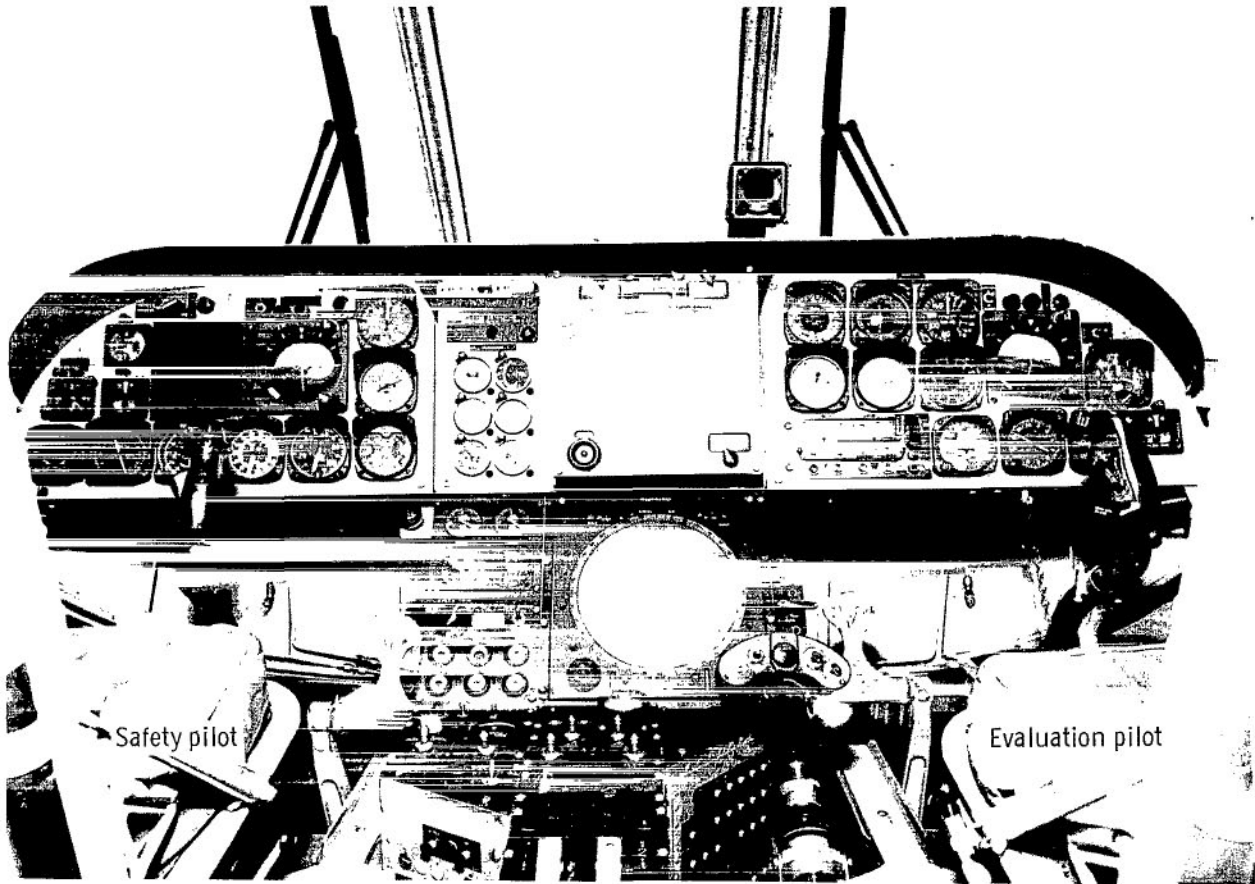

Figure 3.- Cockpit of variable-stability helicopter.   L-67-6733.1

RESULTS AND DISCUSSION

Effect of Angle-of-Attack Stability and Pitch-Rate

Damping Combinations on Handling Qualities

The main emphasis of this investigation was to determine the relationship between angle-of-attack stability and pitch-rate damping as they affect aircraft handling qualities. For this phase of the investigation, the longitudinal control sensitivity remained fixed at $0.3 \frac{\text{rad/sec}^2}{\text{in.}}$ $\left(0.12 \frac{\text{rad/sec}^2}{\text{cm}} \right)$, and the speed stability was held constant at the neutral

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level, $\dfrac{M_{Y_u}}{I_Y} = 0$. These results are presented in the form of constant pilot-rating boundaries in a plot of pitch-rate damping against angle-of-attack stability, as shown in figure 4. It should be noted that the right-hand portion of the $6\frac{1}{2}$ pilot-rating boundary shown in figure 4 is based on an extrapolation of the test data. The pilot ratings and comments associated with each test combination are given in table II.
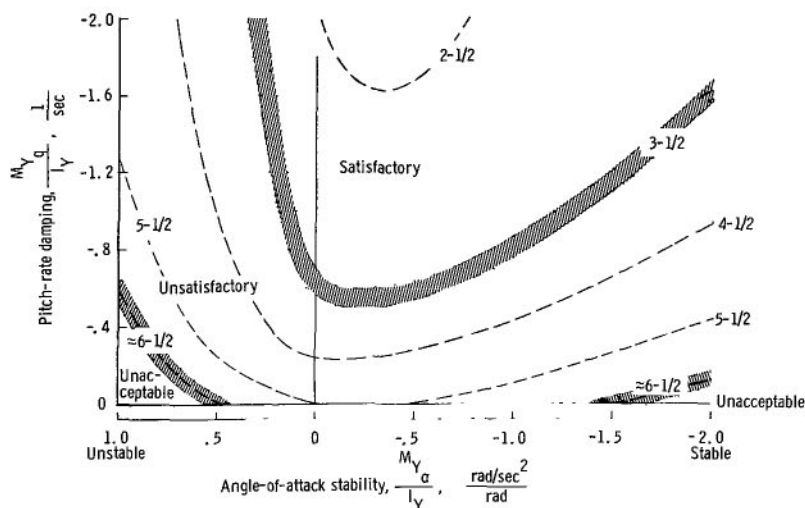

Figure 4.- Pilot-rating boundaries for angle-of-attack stability and pitch-rate damping.

$$\frac{M_{Y_\delta}}{I_Y} = 0.3 \ \frac{rad/sec^2}{in.} \ \left(0.12 \ \frac{rad/sec^2}{cm}\right); \ \frac{M_{Y_u}}{I_Y} = 0.$$

Figure 4 indicates that for any level of damping the best ratings occurred in the neutral to slightly stable angle-of-attack stability region. When the angle-of-attack stability was increased beyond this region into the more stable region, the aircraft characteristics deteriorated because of large trim shifts and increased gust responsiveness. Satisfactory ratings were obtained for slightly unstable angle-of-attack stability levels when sufficient damping was provided. At still higher levels of instability, the lack of a trim condition became more noticeable; consequently, the pilot was forced to monitor attitude very closely and to make small corrective inputs continuously. The resulting increase in workload is reflected by the downrating of the characteristics associated with this unstable region.

Comparisons of Angle-of-Attack Stability and Pitch-Rate

Damping Results With Current Criteria

As noted previously, the handling qualities related to the unstable angle-of-attack stability region were observed to be dominated by the absence of a trim condition. This

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observation suggested the possibility of applying a criterion associated with either a divergent or a weakly convergent aircraft characteristic. Since the pilot-rating boundary in figure 4 approximates a line of constant damping within the low, but stable, angle-of-attack stability region, it appears that the correlation should be related to a pitch-rate-damping criterion. In order to establish an adequate criterion which would apply to the high angle-of-attack stability region, trim changes, gust susceptibility, and the oscillatory nature of the aircraft response would have to be accounted for simultaneously. For correlation purposes, therefore, the plot of angle-of-attack stability against pitch-rate damping (fig. 4) was divided into three regions corresponding to the following levels of angle-of-attack stability:

(1) Unstable region $\left(\dfrac{M_{Y_\alpha}}{I_Y} > 0\right)$

(2) Low stability region $\left(0 > \dfrac{M_{Y_\alpha}}{I_Y} \geqq -0.75\right)$

(3) High stability region $\left(\dfrac{M_{Y_\alpha}}{I_Y} < -0.75\right)$

Unstable region.- The maneuvering response requirement (see section 2.5 of ref. 3) states, in effect, that the time histories of both normal acceleration and pitch angular velocity shall become concave downward within 2 seconds following a longitudinal step input. Qualitative analysis of flight time histories of longitudinal pull and hold maneuvers for test conditions in the vicinity of the left-hand portion of the $3\frac{1}{2}$ pilot-rating boundary of figure 4 indicated (1) that, in this case, the angular-velocity requirement was not critical and, therefore, did not provide correlation with the present results, since the angular-velocity time histories were concave downward well within the 2-second limit and (2) that the normal-acceleration requirement appeared to yield a correlation in this region. Because the number of flight time histories was insufficient to generate the desired boundaries for constant time to become concave downward, the boundaries were computed by using the theory of reference 4 and cross-checked by the theory of reference 5. These computed boundaries are shown in figure 5(a) for values of τ equal to 1, 2, and 3 seconds and for the limiting case where τ approaches infinity. Even though the theory from which the boundaries were computed assumes that the speed remains constant throughout the pull and hold maneuver, this assumption should yield reasonable accuracy for the boundaries which correspond to values of τ up to 2 or 3 seconds. In any event, the computed boundaries would likely be within the uncertainty associated with determining inflection points from actual flight time histories.

Correlations between the time for normal acceleration to become concave downward and the $3\frac{1}{2}$ pilot-rating boundary obtained for combinations of angle-of-attack stability $\left(\dfrac{M_{Y_\alpha}}{I_Y}\right)$ and pitch-rate damping $\left(\dfrac{M_{Y_q}}{I_Y}\right)$ are shown in the unshaded region of figure 5(a). This figure indicates that a criterion based on $\tau = 1$ second would require

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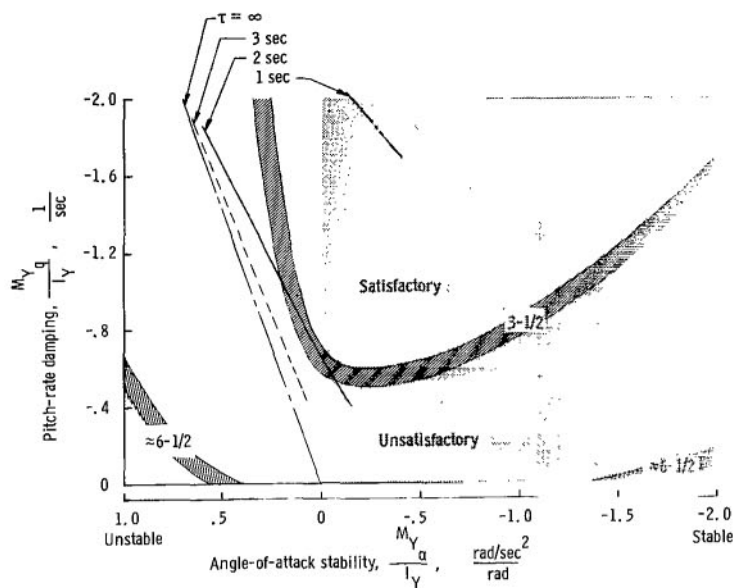
(a) Correlation within the unstable angle-of-attack stability region (unshaded area).
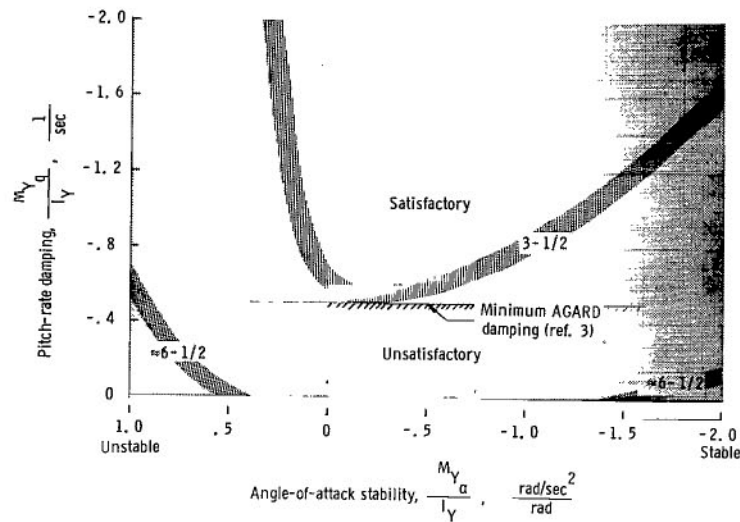
Figure 5.- Correlation of the minimum satisfactory boundary with current criteria. τ = calculated time for normal acceleration to become concave downward.

combinations of $\dfrac{M_{Y_\alpha}}{I_Y}$ and $\dfrac{M_{Y_q}}{I_Y}$ which would be greatly in excess of the minimum satisfactory boundary. By comparison, combinations of $\dfrac{M_{Y_\alpha}}{I_Y}$ and $\dfrac{M_{Y_q}}{I_Y}$ satisfying the 2-second boundary, which corresponds to the requirement of reference 3, provide reasonable correlation with this part of the $3\frac{1}{2}$ boundary, particularly for pitch-rate-damping values between -0.5 and -1.0 $\dfrac{1}{\text{sec}}$. Incidentally, the τ-boundaries converge as the damping is increased and thus indicate that the inflection point on normal acceleration is extremely sensitive to minute changes in $\dfrac{M_{Y_\alpha}}{I_Y}$ and $\dfrac{M_{Y_q}}{I_Y}$ in the high damping region.

Low stability region.- Correlation between the minimum satisfactory damping level specified by current criteria (ref. 3) and that part of the $3\frac{1}{2}$ pilot-rating boundary which falls within the low angle-of-attack stability region is shown in the unshaded area of figure 5(b). It is concluded from this figure that the AGARD damping requirement provides an adequate criterion for the range of angle-of-attack stability between 0 and -0.75 $\dfrac{\text{rad/sec}^2}{\text{rad}}$.
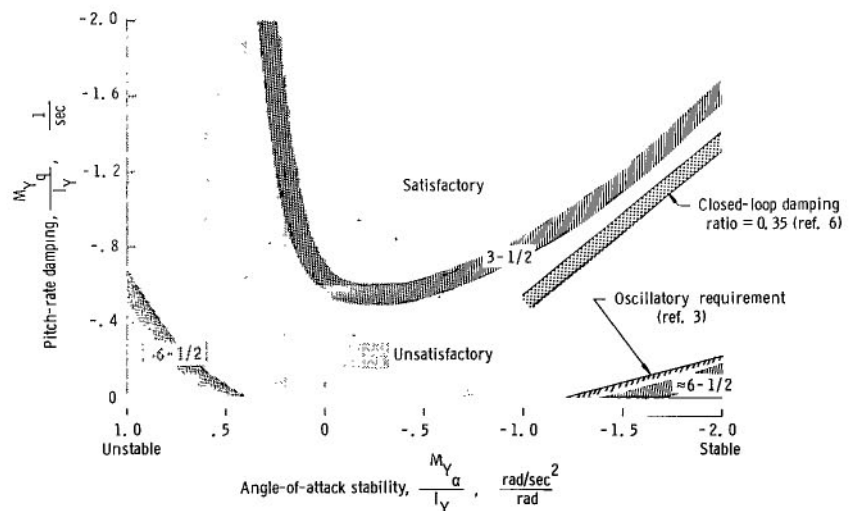
High stability region.- In the high stability region, a potential candidate for correlating the satisfactory combinations of angle-of-attack stability and pitch-rate damping would appear to be the dynamic stability requirement of reference 3. This requirement is stated in terms of the control-fixed oscillatory characteristics wherein a minimum damping-ratio level is specified as a function of the period of oscillation. Combinations of angle-of-attack stability and pitch-rate damping which just satisfy this oscillatory requirement are shown in the unshaded area of figure 5(c). The results indicate that the oscillatory requirement provides very poor correlation with the minimum satisfactory boundary $\left(\text{pilot rating of } 3\frac{1}{2}\right)$ and more nearly corresponds to the minimum acceptable boundary $\left(\text{pilot rating of } 6\frac{1}{2}\right)$ extrapolated from the test data.

Because the results of the present investigation in this high stability region could not be correlated solely on the basis of aircraft characteristics, a closed-loop-type analysis, wherein the pilot is treated as an active part of the control loop, was considered. A partial theory of longitudinal flying qualities based on such a closed-loop analysis was developed in reference 6. Several tentative criteria were developed, one of which suggested that a closed-loop damping ratio of 0.35 should exist for satisfactory handling qualities. Combinations of angle-of-attack stability and pitch-rate damping which result in a closed-loop damping ratio equal to 0.35 are shown in figure 5(c). (The nonequalized pilot transfer function employed in the closed-loop calculations was of the form which is associated with minimum pilot effort; that is, a minimum amount of anticipation is involved in controlling the aircraft.) The closed-loop damping-ratio criterion is seen to provide good correlation with
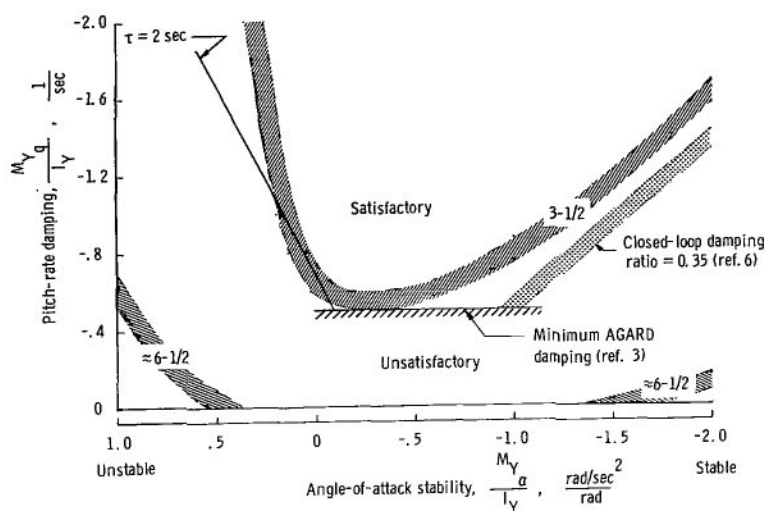

(b) Correlation within the low stability region (unshaded area).

Figure 5.- Continued.

(c) Correlation within the high stability region (unshaded area).

Figure 5.- Continued.

(d) Summary of correlations obtained for the minimum satisfactory boundary.

Figure 5.- Concluded.

$\left(0.13 \dfrac{\text{rad/sec}^2}{\text{m/sec}}\right)$, the speed change during the task was reduced from 30 to 20 knots to allow a sufficient control-power margin. (The pitch control power was limited to 1.0 rad/sec², and the pilot would have run out of forward control prior to obtaining the 30-knot increment.)

Pilot ratings corresponding to variations in speed stability are shown in figure 6. This figure illustrates that the optimum level of speed stability was approximately $0.005 \dfrac{\text{rad/sec}^2}{\text{ft/sec}} \left(0.016 \dfrac{\text{rad/sec}^2}{\text{m/sec}}\right)$. As the level of speed stability was increased, gust susceptibility, oscillations, and trim changes contributed more or less equally to the degradation in pilot rating. Unstable values of speed stability caused a rapid deterioration in handling qualities. Attitude control was very difficult in the unstable region and, for the highest speed instability tested, the pilot commented that he could easily lose control of the aircraft.

Effect of Longitudinal Control Sensitivity

The effect of longitudinal control sensitivity on handling characteristics was investigated for four combinations of angle-of-attack stability and pitch-rate damping. (See fig. 7.) The sensitivity was varied between 0.1 and 0.6 $\dfrac{\text{rad/sec}^2}{\text{in.}}$ $\left(0.04 \text{ and } 0.24 \right.$ $\left. \dfrac{\text{rad/sec}^2}{\text{cm}}\right)$. Pilot ratings as a function of sensitivity are presented in figure 7, which

the results of the present study in this region. In figure 5(d), the correlations presented in this section are summarized.

Effect of Speed Stability

Changes in speed stability were investigated for four combinations of angle-of-attack stability and pitch-rate damping. (See fig. 6.) During this phase of the flight investigation, trim changes were primarily related to the speed-change portion (40 to 70 knots) of the task. For the highest speed stability, 0.04 $\dfrac{\text{rad/sec}^2}{\text{ft/sec}}$
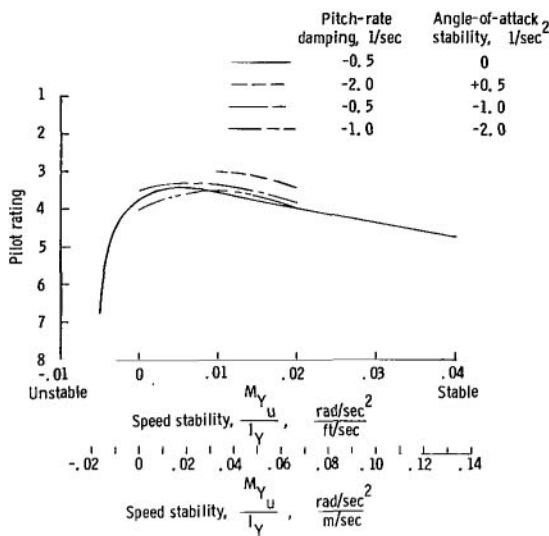
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Figure 6.- Variation in pilot rating with speed stability.
$$\frac{M_{Y_\delta}}{I_Y} = 0.3 \ \frac{rad/sec^2}{in.} \ \left(0.12 \ \frac{rad/sec^2}{cm}\right).$$
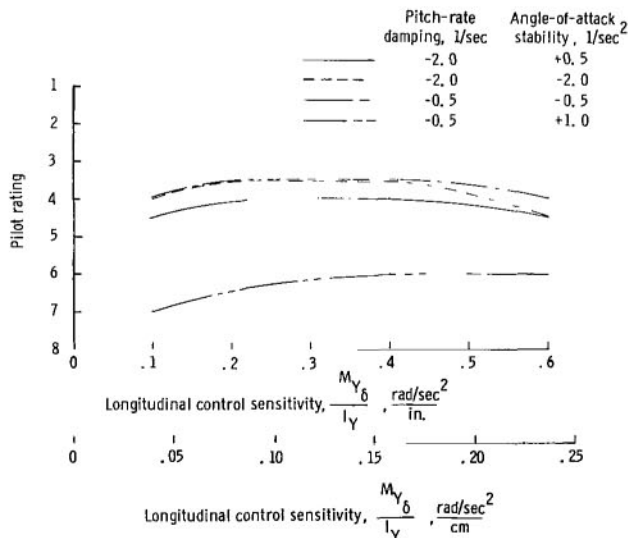

Figure 7.- Variation in pilot rating with longitudinal control sensitivity. $\frac{M_{Y_u}}{I_Y} = 0.$

shows that the range between 0.2 and $0.5 \ \frac{rad/sec^2}{in.} \ \left(0.08 \ and \ 0.20 \ \frac{rad/sec^2}{cm}\right)$ was considered optimum. For the lowest value tested, $0.1 \ \frac{rad/sec^2}{in.}$, the downrating was caused primarily by the large stick displacements required. This trend was also observed in reference 7 in which control sensitivities below $0.1 \ \frac{rad/sec^2}{in.}$ resulted in a very rapid degradation in pilot rating.

For the highest values tested, the slight downrating which occurred was based on the pilot's inability to maintain an accurate stick trim position. This stick-centering problem was complicated by a deficiency in the trim system which prevented precise stick force trimming and resulted in the pilot's having to hold a slight stick force to maintain trim. Although the results show a wide range of satisfactory control sensitivities, experience has shown that undesirable control-system characteristics, such as friction, which sometimes enter into a control-system design, tend to be aggravated by high values of sensitivity. Therefore, it is recommended that caution be used when the control sensitivity of the design falls at the higher end of the range investigated.

CONCLUSIONS

A flight investigation was conducted under simulated IFR conditions to determine the effects of gross changes in several longitudinal stability and control parameters on handling qualities

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requirements. From the results obtained by using a variable-stability helicopter, the following conclusions are drawn:

1. Neutral to slightly stable angle-of-attack stability was found to be most satisfactory by the pilot, regardless of the level of pitch-rate damping. Slightly unstable values of angle-of-attack stability were considered satisfactory when sufficient pitch-rate damping was provided.

2. Combinations of angle-of-attack stability and pitch-rate damping which provided minimum satisfactory handling qualities were generally in good agreement with current specifications (AGARD Rept. 408) for angle-of-attack stability levels less stable than $-0.75 \frac{rad/sec^2}{rad}$. For values of angle-of-attack stability more stable than $-0.75 \frac{rad/sec^2}{rad}$, the present results did not correlate with current specifications but did correlate well with a criterion based on a closed-loop analysis of pilot-vehicle combination.

3. The optimum level of speed stability was found to be about $0.005 \frac{rad/sec^2}{ft/sec}$ $\left(0.016 \frac{rad/sec^2}{m/sec}\right)$. Unstable values of speed stability caused pilot ratings to deteriorate rapidly.

4. The optimum range of longitudinal control sensitivity was found to occur between 0.2 and $0.5 \frac{rad/sec^2}{in.}$ $\left(0.08 \text{ and } 0.20 \frac{rad/sec^2}{cm}\right)$.

Langley Research Center,
    National Aeronautics and Space Administration,
        Langley Station, Hampton, Va., August 28, 1967,
           721-06-00-03-23.

APPENDIX

MECHANIZATION OF SIMULATION

The signal flow diagram in figure 8 shows the essential features of the simulation technique and represents the mechanization of the longitudinal dynamics as given by the following equation:

$$\dot{q} = \frac{M_{Y_\delta}}{I_Y} \delta_Y + \frac{M_{Y_q}}{I_Y} q + \frac{M_{Y_\alpha}}{I_Y} \alpha + \frac{M_{Y_u}}{I_Y} u$$

As indicated in the figure, the aerodynamic angular-velocity damping was simulated by feeding back a signal proportional to the model angular velocity into the summing junction of integrator 1. The simulation of speed stability was accomplished by feeding a signal proportional to the forward component of the aircraft velocity into integrator 1. Similarly, the angle-of-attack stability was simulated by feeding back a signal proportional to the angle of attack as sensed by a nose boom vane.
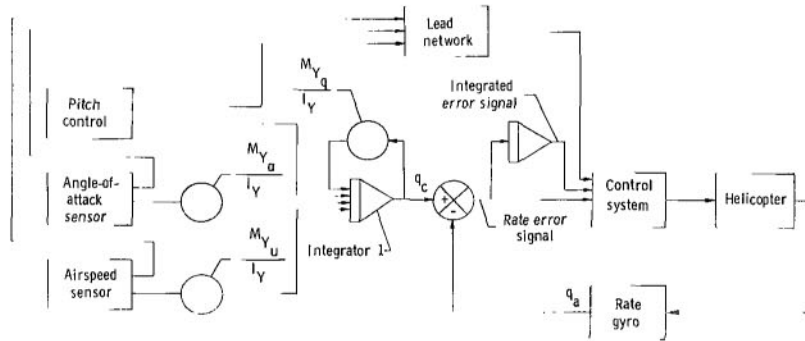

Figure 8.- Simplified signal-flow diagram for longitudinal axis.

A corresponding simulation technique was used for the lateral and directional degrees of freedom in accordance with the following equations:

$$\dot{p} = \frac{M_{X_\delta}}{I_X} \delta_X + \frac{M_{X_p}}{I_X} p$$

$$\dot{r} = \frac{M_{Z_\delta}}{I_Z} \delta_Z + \frac{M_{Z_r}}{I_Z} r + \frac{M_{Z_\beta}}{I_Z} \beta$$

The characteristics of the lateral-directional degrees of freedom were selected to provide minimum satisfactory handling characteristics $\left(\text{pilot rating of } 3\frac{1}{2}\right)$. The values

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employed during this study were based on the results of reference 8 and are as follows:

$$\frac{M_{Z_\delta}}{I_Z} = 0.2 \ \frac{rad/sec^2}{in.} \ \left(0.08 \ \frac{rad/sec^2}{cm}\right)$$

$$\frac{M_{Z_r}}{I_Z} = -1.0 \ \frac{1}{sec}$$

$$\frac{M_{Z_\beta}}{I_Z} = 0.4 \ \frac{rad/sec^2}{rad}$$

$$\frac{M_{X_\delta}}{I_X} = 0.3 \ \frac{rad/sec^2}{in.} \ \left(0.12 \ \frac{rad/sec^2}{cm}\right)$$

$$\frac{M_{X_p}}{I_X} = -1.5 \ \frac{1}{sec}$$

The vertical degree-of-freedom characteristics were not altered for the current investigation, and thus the characteristics of the basic aircraft are applicable. Other stability derivatives, which are representative of the basic aircraft and were unaltered in these tests, are essential for the analytical computations included in this report. They are the following:

$$\frac{F_{X_u}}{m} = -0.025 \ \frac{1}{sec}$$

$$\frac{F_{Z_w}}{m} = -0.38 \ \frac{1}{sec}$$

$$\frac{F_{Z_\delta}}{m} = 0.23 \ \frac{ft/sec^2}{in.} \ \left(0.028 \ \frac{m/sec^2}{cm}\right)$$

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TABLE I.- EXPANDED NASA PILOT-RATING SYSTEM

Operating conditions	Adjective rating	Numerical rating	Description	Added descriptive phrases	Task performance	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum			Yes	Yes
		2	Good, pleasant to fly	Very stable, disturbances well damped	Precise	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Stable, not easily disturbed	Precise, most of time	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Occasional large, but controllable upsets	Few errors	Yes	Yes
		5	Unacceptable for normal operation	Distractions not tolerable, full-time control required	Difficult to maintain accuracy	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Must concentrate on a single (pitch) axis only	Poor	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	Difficult to control attitude, with possible loss of control	Ignored	No	Doubtful
		8	Unacceptable – dangerous	Very easy to lose control (loss of control imminent)		No	No
		9	Unacceptable – uncontrollable			No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape			No	No

[1]Failure of stability augmenter.

TABLE II.- PILOT RATINGS AND COMMENTS FOR ANGLE-OF-ATTACK STABILITY

Configuration	$\frac{M_{Y_q}}{I_Y}$, 1/sec	$\frac{M_{Y_\alpha}}{I_Y}$, $\frac{rad/sec^2}{rad}$	Pilot rating	Summary of pilot comments
A	-2.0	1.0 (Unstable)	$4\frac{1}{2}$ to 5	Difficult to stabilize attitude. Tendency to overshoot when changing attitude or correcting for a disturbance. Too responsive to gusts. The work load was high and enough distractions (tuning radios, etc.) could lead to large excursions in attitude.
B	-2.0	0.5 (Unstable)	4 to $4\frac{1}{2}$	Small pitch corrections were difficult to make and it was impossible to establish a trim condition. Pilot control inputs coupled with the aircraft response and resulted in a low frequency oscillatory mode which was aggravated by disturbances. There was a noticeable longitudinal trim change produced by angle-of-attack changes (power) which made the task more demanding. This trim change was in the "wrong" direction (i.e., a nose down pitching moment for an increase in power).
C	-2.0	0	2 to $2\frac{1}{2}$	This configuration was very comfortable and required an average workload to perform the task. Disturbances had a negligible effect.
D	-2.0	-1.0 (Stable)	3 to $3\frac{1}{2}$	Noticeable control inputs were required to change attitude (too well damped) or the intended correction ended up short of the desired change. Retrimming for steady-state angle-of-attack changes was required but easily accomplished. Disturbances were easy to control.
E	-2.0	-2.0 (Stable)	$3\frac{1}{2}$	This configuration was fairly comfortable and the ability to perform the task was good. Control sensitivity was a little low. There was a need to retrim slightly for trim changes due to angle-of-attack changes.
F	-1.0	1.0 (Unstable)	$5\frac{1}{2}$ to 6	Easy to start a pilot-induced oscillation (PIO) and overcontrol. Had to keep inputs small and monitor pitch attitude all the time. Appeared to be too sensitive. Trim changes with angle of attack added to the work-load. Speed control was marginal.
G	-1.0	0.5 (Unstable)	$4\frac{1}{2}$	This configuration appeared to be a little too sensitive and started to oscillate about the desired attitude because of disturbances and pilot overcontrolling.
H	-1.0	0	3 to $3\frac{1}{2}$	This configuration was a little too sensitive and minor overcontrolling resulted.
I	-1.0	-0.5 (Stable)	$3\frac{1}{2}$	The response appeared sluggish at times and good at other times. There was a slight tendency to overcontrol. The main problem was controlling trim changes. Could do a good job on the task.
J	-1.0	-1.0 (Stable)	$3\frac{1}{2}$	Slight tendency to overcontrol for large inputs. There was a constant need for small corrections. Large corrections would generally result in a short 1-cycle overshoot. The response was good for small inputs.
K	-1.0	-2.0 (Stable)	$4\frac{1}{2}$	This configuration was confusing because the response to control inputs varied between good and sluggish. Pitch control inputs resulted in short-period lightly damped oscillations. Trim changes were in the "right" direction but were too large. Although these characteristics increased the workload, the task was not difficult to perform.

Configuration	$\dfrac{M_{Y_q}}{I_Y}$, 1/sec	$\dfrac{M_{Y_\alpha}}{I_Y}$, $\dfrac{rad/sec^2}{rad}$	Pilot rating	Summary of pilot comments
L	-0.5	1.0 (Unstable)	6 to $6\frac{1}{2}$	It was difficult to hold an attitude and very easy to overcontrol. This difficulty was alleviated somewhat by using fingertip control. Overall, this could be a dangerous configuration if the pilot were distracted to any extent. The large negative (nose down) pitching moment associated with power increases (angle-of-attack changes) added to the workload.
M	-0.5	0.5 (Unstable)	5 to $5\frac{1}{2}$	The ability to hold speed and altitude was poor. (Only a brief look was taken at this configuration and the instrument pattern was not flown; consequently, detailed comments were not obtained.)
N	-0.5	0	$3\frac{1}{2}$ to 4	Considerable attention was required to control speed and attitude. Could do a fair job on the instrument pattern. Disturbances had a negligible effect on the workload.
O	-0.5	-0.5 (Stable)	$3\frac{1}{2}$ to 4	Although there were not too many disturbances, the response to gusts was large compared with the response to control inputs and the control was sluggish at times. There was a slight tendency to overcontrol. The pitching moments (trim shift due to angle-of-attack changes) appeared to lag the power changes by approximately 5 seconds and made airspeed control very difficult. The lack of a precise pitch trim system contributed to the problem.
P	-0.5	-1.0 (Stable)	4	This configuration appeared to be too sensitive to gusts. A slow but continuous oscillation in pitch resulted. Difficult to stay in phase with the gust response and had to constantly make control inputs.
Q	-0.5	2.0 (Stable)	5 to $5\frac{1}{2}$	The response to gusts was too great. At times there was a tendency to overcontrol and PIO for a few cycles after a small disturbance. Sometimes the sensitivity was too much and other times it was good.
R	-0.25	1.0 (Unstable)	7	This configuration required fingertip control inputs only and constant attention to the pitch axis. On an ideal calm day one could do a fair job of instrument flying, but a large amount of controlling would be required.
S	-0.25	0.5 (Unstable)	6	Attitude control was poor. The initial response to control inputs and disturbances was too rapid and required constant attention to attitude.
T	-0.25	0	$4\frac{1}{2}$	This configuration was a little sensitive for small inputs and overcontrolling which resulted in a continuous oscillation about the desired attitude occurred.
U	-0.25	-0.5 (Stable)	5	Too responsive to gusts and control inputs. Very easy to overcontrol and PIO for 1 cycle. The overall work load was high. Control of only the pitch axis would not be difficult, but there were too many other distractions to perform the instrument task very well.
V	-0.25	-1.0 (Stable)	5 to $5\frac{1}{2}$	Too responsive to disturbances and control inputs. A continuous long-period oscillation about the desired attitude resulted. There was a tendency to overcontrol.

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